The Energy and Climate Change Implications of Different Music Delivery Methods

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Summary

The impacts of information and communications technology (ICT) on the environment have been a rich area for research in recent years. A prime example is the continuing rise of digital music delivery, which has obvious potential for reducing the energy and environmental impacts of producing and delivering music to final consumers. This study assesses the energy and carbon dioxide (CO_2) emissions associated with several alternative methods for delivering one album of music to a final customer, either through traditional retail or e-commerce sales of compact discs or through a digital download service. We analyze a set of six (three compact disc and three digital download) scenarios for the delivery of one music album from the recording stage to the consumer's home in either CD or digital form. We find that despite the increased energy and emissions associated with Internet data flows, purchasing music digitally reduces the energy and carbon dioxide (CO_2) emissions associated with delivering music to customers by between 40% and 80% from the best-case physical CD delivery, depending on whether a customer then burns the files to CD. Despite the dominance of the digital music delivery method, however, there are scenarios by which digital music performs less well, and these scenarios are explored. We suggest future areas of research, including alternative digital media services, such as subscription and streaming systems, for which Internet energy usage may be larger than for direct downloads.

Introduction

Discussions about the environmental effects of information and communications technology (ICT) almost invariably focus on the direct electricity used by this equipment, which is easily measurable and has been growing over the past few decades (Harris et al. 1988; Koomey et al. 1996; Kawamoto et al. 2002; Roth et al. 2002, 2006).

The often-ignored indirect effects are also important, however. ICT has at least three important indirect effects on resource use and environmental impacts:

- Dematerializing products and services: Moving bits instead of atoms is always less energy-intensive and environmentally damaging (Matthews et al. 2000; Atkyns et al. 2002; Turk et al. 2003).
- Becoming smarter: Using ICT to improve control of business and industrial processes reduces both costs and environmental impacts while also improving productivity.
- Becoming wealthier: ICT increases economic growth (because it reduces costs and improves productivity) and makes the society wealthier than it would otherwise be.

The size of these effects is rarely measured, in part because of the difficulty of doing so. To accurately assess environmental effects of dematerialization and becoming smarter, one must conduct a full life cycle assessment (LCA) for a well-defined business process or product.

Clean examples that allow for consistent comparisons are relatively rare, but in this analysis we characterize environmental impacts for dematerialization, focusing on delivery of a music album by digital download versus shipment of a CD. This particular example allows an order of magnitude assessment of the benefits of moving bits instead of atoms.

Background

The past 2 decades have seen the emergence of new ways to sell and deliver products that are different from traditional retailing. These methods include “e-tail” (buying products online and shipping them directly to the customer), digital downloads (for information products, e.g., music), and subscription services for music and other digital products.

The environmental effects of ICT have been an active topic of research for many years. Past work has discussed in general terms the energy and environmental benefits of telecommuting over traditional commuting (Atkyns et al. 2002). Several authors have compared the energy and environmental emissions associated with online retail (henceforth “e-commerce”) with traditional retail methods. Matthews and colleagues (2001) compared book purchasing by e-commerce and traditional retailing, and Hendrickson and colleagues (2005) updated and summarized this comparison. Matthews and colleagues (2002) completed an LCA study reviewing energy and cost impacts of logistics networks for the retail of books in Japan and the United States. Abukhader (2004) proposed a methodology for assessing “green supply chains” for e-commerce. Toffel and Horvath (2004) examined delivery of print products by digital means. Sivaraman and colleagues (2007) examined alternative logistics systems for DVD rental.

This article differs from past studies of the e-tail/retail question by focusing on dematerializing products themselves instead of just analyzing the route a particular product takes from producer to consumer. Although the general results for past studies have indicated that purchasing items online could lead to a slight improvement in energy efficiency over traditional retail methods (Matthews et al. 2001; Sivaraman et al. 2007), we focus here on a product only made possible in the last decade: the provision of music from recording process to digital music player or CD player. We also, however, consider potential consumer preferences for physical goods by including the possibility of burning digital files to CD.

Typical music supply chains have consisted of studio recording of albums by artists, publication of these albums onto the prevalent media of the time (currently CDs), and movement of this tangible good from production and publishing through to a final consumer in the home. Although some previous work has been done on such dematerialized products—for example, a study on the material intensity of digital music and another examining the experience of reading printed media online (Turk et al. 2003; Toffel and Horvath 2004; Hogg and Jackson 2008)—to our knowledge, this is the first study to directly compare the energy and greenhouse gas (GHG) impacts of downloading music versus purchasing CDs by a retail or e-tail method.

There are clear potential energy and GHG savings from delivering music digitally, as opposed to the typical supply chain of the past: the energy and emissions associated with producing the CD and packaging it, as well as the transportation chain to deliver this good. These savings are offset, however, by the energy and emissions associated with network and data center usage to deliver the music digitally, as well as those of recordable media and media storage if the user burns music to a CD. In this article, we detail six scenarios of potential music delivery, three using traditional CD media and three using digital media. The goal and scope of the analysis are to compare these scenarios from an energy and GHG perspective. The next section describes these scenarios as well as data sources, assumptions, and methods. We then detail the results of delivering music by the six scenarios and, finally, discuss the implications and limitations of the study.

Methods and Assumptions

We define and analyze six scenarios by which a functional unit of one album of music could move from recording through distribution to a final consumer of music:

1. album published on CD and delivered by traditional retail methods
2. album published on CD and delivered by light-duty truck through an online e-tail provider
3. album published on CD and delivered by express air through an online e-tail provider
4. album downloaded as MP3 or MP4 files from an online music service and used digitally
5. album downloaded as MP3 or MP4 files from an online music service and burned to CD-R for digital and CD use (no CD packaging)
6. album downloaded as MP3 or MP4 files from an online music service, burned to CD-R for digital and CD use, and stored in individual CD packaging (i.e., slimline jewel cases)

Each scenario is summarized further below.

Figure 1 shows a visual representation of the transportation chain for Scenario 1, traditional retail. The product begins at the manufacturer, from which it is shipped by heavy-duty truck to the wholesale warehouse. The product sits in the warehouse (for simplicity, we assume only one warehouse, owned by the retailer) for a certain amount of time, until the product is in demand by the retail store, and we assume in the base case that it is then trucked directly to the store, packaged in bulk. Although in some cases a shipment may go through a secondary warehouse belonging to the retailer (or an intermediate distribution warehousing facility) before it is shipped to the actual store, we assume direct delivery from the wholesale warehouse to the retail store. Individual consumers drive by car from their home to the nearest retail store to pick up the product and then return home. Of course, the consumer trip to the retail store could include multiple stops or purposes, and this is discussed below in more detail. It should be noted that because we assume that the recording process itself is similar in all six scenarios, we do not analyze it.

Figure 2 shows the transportation chain diagram for the e-tail or e-commerce model, Scenarios 2 and 3. In this model, the product begins at a manufacturer and is delivered to a distributor warehouse, again by heavy-duty truck. Although this step is not shown as a part of the transportation flow in figure 2, a customer shops for and buys a product on the e-commerce company Web site. After receiving information from the e-commerce company's data center that the product has been ordered and needs to be shipped, the distributor warehouse individually packages and sends the product to the collecting and sorting distribution center through a parcel service, either by truck (Scenario 2) or by airplane (Scenario 3), depending on the online consumer's preferences for delivery time. The product is then

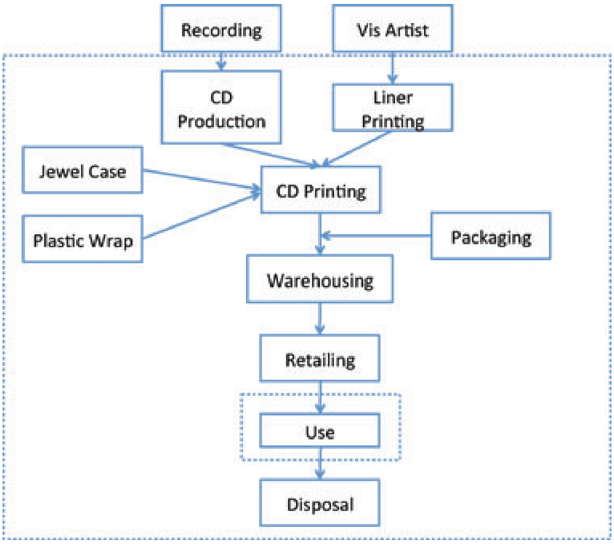

Figure 1 Traditional retail product flow diagram (Scenario 1). Vis Artist = visual artist.

taken to the consumer's home by a light-duty delivery truck (we assume a 20,000 lb [approx. 9,070 kg] truck) that is also carrying other products.

As can be seen in figures 1 and 2, the initial stages in the product delivery (manufacturing, transport to first warehouse, and storage at first warehouse) are similar for both retail models. The time a package spends in a collecting and sorting distribution center after the wholesaler warehouse and before the distribution center is assumed to be small relative to the time spent in a wholesaler's warehouse. Thus, we assume that the site energy use at the collection and sorting centers per package is relatively small compared with the warehouse energy use per package. The main differences in the transportation chains are from the warehouse to the retail store or distribution center and from the retail store or distribution center to the consumer. In addition, some potentially important nontransportation differences exist between the systems: energy usage in the data center to run the e-commerce Web site,

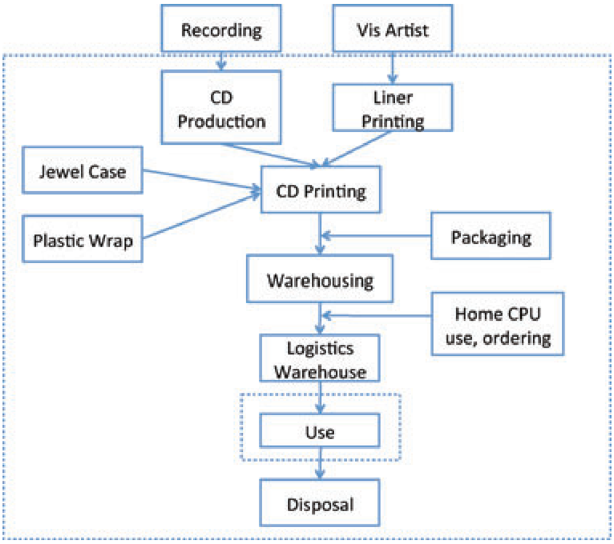

Figure 2 E-commerce product flow diagram (Scenarios 2 and 3). Vis Artist = visual artist; CPU = personal computer.

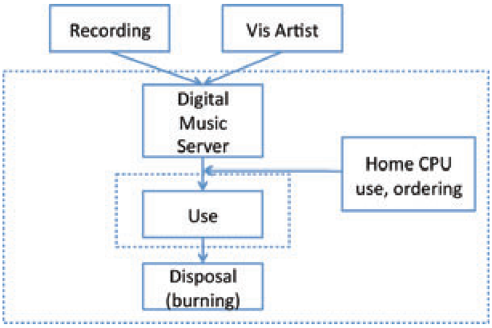

Figure 3 Download flow diagram (Scenarios 4, 5, and 6). Vis Artist = visual artist; CPU = personal computer.

different uses of packaging (i.e., individual packaging vs. bulk packaging) from the wholesaler to the consumer, and energy use in the traditional retail store.

The possibility of downloading the album directly from an online music distributor changes the e-commerce and retail models considerably. This simpler chain is shown in figure 3 and represents Scenarios 4, 5, and 6. Here, files from recording are sent directly to digital storage of the online music site and downloaded through data center communication when a customer shops online for the album; this constitutes the complete logistics chain for Scenario 4. One of the issues with analyzing online music systems, however, is that online music customers can use their downloaded music in various ways—digitally on the computer used for downloading; on a digital music player, such as Apple's iPod or Microsoft's Zune; or burned to a CD-R for use in a traditional CD player (Turk et al. 2003; Bottrill et al. 2008). To capture these different uses, we develop three scenarios, one where the customer buys bulk CD-Rs (assumed to be sold in packs of 50) and burns the album to disc, and another where the customer does this and also purchases bulk CD-R packaging to protect the CD. We ignore any potential differences in lifetime between factory-printed CDs and CD-Rs. To simplify this scenario, we assume that the packaging used by the customer is similar to that used in the production of the physical CD from Scenarios 1–3.

These different uses make exact comparison between the systems difficult, as downloading an album does not directly lead to the same type of music usage as purchasing a CD. Purchasers of CDs, however, are now able to easily convert music to digital format, and purchasers of digital music can store it on CD media (albeit usually with lower fidelity). Thus, we assert that including the production of a CD-R (Scenarios 5 and 6) and individual CD-R packaging in cases (Scenario 6) leads to full equivalence with the CD purchase, as Scenarios 1, 2, 3, 5, and 6 can all lead to the same list of potential uses, including both CD and digital listening on various systems. Of course, this is a simplistic representation of a complex system of consumer behavior—a customer is more likely to purchase digital music if he or she owns a digital music player and is more likely to purchase a digital music player if he or she owns digital music. In the absence of data on how consumers use different music types differently, however, it is difficult to imagine any more complex assumptions about consumer behavior leading to more accurate results, and thus we focus here on consistency of the functional unit.

The primary remaining differences in these scenarios are (by assumption):

- Most online music consumers are unconcerned with the loss of fidelity associated with digitally downloaded music.
- Online music consumers are more likely to buy CD-Rs and CD cases in bulk (i.e., assumed packages of 50 CD-Rs and cases) and online (similar to Scenarios 2 and 3).

In summary, the systems under consideration include the following stages within the comparative study boundary:

- warehouse energy usage (Scenarios 1–3)
- electricity use at home computer to place e-commerce order (Scenarios 2–6)
- transportation from the wholesale warehouse to the retail store, distribution center, or retail warehouse (Scenarios 1–3)
- "last-mile" transportation from local distribution center to customer home or from retail store to customer home (Scenarios 1–3)

- data center electricity usage to run e-commerce and online music sites (Scenarios 2–6)
- individual versus bulk cardboard packaging (Scenarios 1–3 and 5–6)
- energy use in traditional retail store (Scenario 1)
- Internet network electricity usage for download (Scenarios 4–6)

In contrast, the following stages or parameters are not included in this comparative study because they either are likely to be small compared with foreground processes or are similar between the systems:

- energy use of corporate headquarters of retail and e-commerce companies
- noncardboard packaging
- production of listening systems (iPod or Zune, CD players, etc.)
- energy use of music listening

For summary purposes, we include Supplementary Table S1–1 in the Supplementary Material on the Web to show these assumed boundaries by scenario. Each process included within the system boundary requires different data and assumptions. Thus, we discuss each process individually in the following sections. In general, we model uncertainty using probabilistic analysis (Monte Carlo simulation) with triangular distributions, where the most likely value is estimated from existing data and minimum and maximum likely values are estimated or taken as the largest and smallest available data points. We chose Monte Carlo simulation rather than simple uncertainty bounds because many of the variables used have considerable uncertainty ranges, and simple minimum—maximum ranges would be difficult to interpret. Simulation using simple assumed distributions, such as we have done here, gives a more easily interpretable range of overall uncertainty because it explores interactions between the different variables' uncertainties. It should be stressed, however, that most of the distributions used here are assumed, and thus probabilistic results should be taken as approximate.

Data Sources

For transparency, we show all assumed input parameters and a detailed discussion of our data sources in the Supplementary Material on the Web. A summary is shown in the following section.

Fuel Carbon and Energy Intensity

Supplementary Table S1–2 in the Supplementary Material on the Web shows the assumed energy content and carbon content of different fuels. We assume a U.S. national average emissions factor for electricity of 650 grams of carbon dioxide per kilowatt-hour (g CO_2/kWh) as the base case.[1] Given the large variance in electricity emissions factors in different regions of the United States and in different countries, however, we assume a distribution from 300 to 900 g CO_2/kWh, with a mean of 650 g CO_2/kWh. This represents a reasonable range of variation both within the United States (Weber et al. 2009b) and between country averages across the globe (World Resources Institute 2007), so that all potential variability of production location is included. Electricity-based energy is converted to primary energy equivalents on the basis of the International Energy Agency (IEA) substitution method, which represents an adjustment for the initial amount of energy or fuels needed to generate electricity in electric power plants (IEA 2008). In general, we assume a 33% efficiency for converting primary energy to delivered site electricity, which is typical of governmental sources (EIA 2008).

CD and CD Packaging Production

Several data were gathered on the production of CDs and CD-Rs (Frischknecht and Rebitzer 2005; U.S. Census 2005; Bottrill et al. 2008; Green Design Institute 2009; Liverman 2009). CDs used in the publishing industry are assumed to be similar to CD-Rs, for lack of better data. These data yield average production impacts of 4.3 megajoules (MJ) primary energy (range = 3.6–5)[2] and 240 grams of carbon dioxide (g CO_2; range = 200–300) per CD produced.

A wide variety of CD packaging systems are in current use, and data were taken from a newly published study comparing the life cycle GHG impacts of these packaging types (Liverman 2009). We thus assume a range of impacts for the different types of packaging to show the variation (60 g CO_2/package to 1,200 g CO_2/package) in Scenarios 1–3, and we take a mean value from Ecoinvent data for the production of an assumed mass of polystyrene plastic for a jewel case ($\sim$77 g [Bottrill et al. 2008]), which yields 380 g CO_2. For Scenario 6, we assume that users purchasing their own CD-R packaging will choose slimline jewel cases, as opposed to the broad range of packaging options analyzed by Liverman (2009).

Shipping Packaging

For packaging in Scenarios 1, 2, and 3 we assume that the main difference between systems is in the amount of cardboard used for shipping. Energy and emissions from plastic and paper packaging materials are assumed to be ignorable compared with cardboard. Sizes of cardboard per functional unit are estimated as shown in the Supplementary Material on the Web. Data on the energy and CO_2 intensities of corrugated cardboard are taken from the U.S. Environmental Protection Agency's (EPA's) Waste Reduction Model (EPA 2009). These values were also checked for consistency with the Environmental Defense Fund's (EDF's) Paper Calculator 2.0; they were in agreement to one significant figure (see Supplementary Appendix S1–2 in the Supplementary Material on the Web; Environmental Defense Fund 2009).

Distribution and Final Delivery

Although the distance from warehouse to local distribution center or retail store is assumed to be similar, given no better information, the distance is still relevant, because the model energy intensity varies between road and air transport, as shown in Supplementary Table S1–3 in the Supplementary Material on the Web (Burnham et al. 2006; Facanha and Horvath 2006). The distance was taken from a previous study of e-commerce logistics (Weber et al. 2009a), which reported distributions for ground and air shipping. The CD is assumed to weigh 1 lb (approximately 450 g) with packaging. For reference, Bottrill and colleagues (2008) report unpackaged CDs to weigh 108 g. We took all modal energy intensities from the GREET 2.7 model from Argonne National Laboratory (see Supplementary Table S1–3 in the Supplementary Material on the Web [Burnham et al. 2006]).

For the final delivery ("last mile") portion of the logistics chain, data on total system energy per package were taken from a large commercial delivery company (UPS 2007). The systemwide energy use per package was 28.1 MJ/package from this data set, but this represented all energy, not just "last-mile" energy. We used the percentage of energy use from diesel to approximate the last-mile energy intensity (10 MJ/package). To check this assumption, we also gathered data from local interviews of delivery truck drivers, who gave a distribution of packages delivered per day and miles driven from the local distribution center. These data (ranging from 0.1 to 1 mile per package delivered) were combined with the energy efficiency of a 20,000-lb (approximately 9,070 kilograms [kg]) delivery truck, given by Davis and Diegel (2007) as 11 megajoules per kilometer (MJ/km), which produced a per-package estimate range of 2 to 18 primary MJ/package, which was used as the assumed minimum—maximum range of the distribution.

Customer Transport to the Retail Store

The energy and emissions associated with customer transport to the retail store were modeled according to the equation shown below:

$$E/item = \frac{(mi)\,(E/gal)}{(mi/gal)\,(p/veh)\,(items/p)} \qquad (1)$$

where E is energy or emissions, *mi* is round trip miles between the customer home and the retail store, *mi/gal* is the fuel economy of the vehicle, *p/veh* is the number of persons in the vehicle, and *items/p* is the number of items purchased per person. Each of the parameters in equation (1) was treated parametrically or probabilistically. We assumed a minimum of 2 miles (3.2 km) driven and a maximum of 20 (32 km). The mean value was taken from the 2009 National Household Travel Survey (NHTS), which gave a round trip of 14 miles (23 km) for shopping purposes (DOT 2002). This number represents the average round-trip shopping distance any vehicle traveled in 2009. The average on-road fuel economy of the U.S. fleet was assumed to be 22 miles/gallon (0.11 liters per kilometer [L/km]; Davis and Diegel 2007), with a minimum of 10 miles/gallon and a maximum of 30. The mean number of persons per vehicle was also taken from the NHTS, which gave a mean estimate of 1.5 person-trips/vehicle-trip for shopping purposes, with a minimum of 1 and a maximum of 2. We assumed the same distribution for items per person on each trip, on the basis of plausibility. It should be noted that this method implicitly assumes that allocation per item (or separate store, in the case of multiple items per store) is the proper method for allocating the energy used in customer transport. The resulting distribution given these assumptions was triangular, with a mean of 1.8 kg of equivalent carbon dioxide (CO_2e) per item and a 95th percentile range of 0.1 to 7 kg CO_2e/album.[3]

For the probabilistic analysis, it was assumed that the number of items purchased in a trip was correlated with distance the customer had to drive to the store, because a person who lives far from a store will likely purchase more items per trip. It was further assumed that the customer's driving distance was correlated with the distance of the last mile delivery for e-commerce shipments (because those households that are further from a retail store likely are also further from a distribution center).

Other researchers have used economic allocation, but we believe the model above to be more physically related to the process of driving than money spent per stop (Williams and Tagami 2003). Because customer transport represents a large proportion of total gate-to-consumer energy use and GHG emissions, however, we checked the validity of our assumptions with an alternative (economic) allocation scheme. Using the 2008 consumer expenditure survey of the United States, we found a range of total annual expenditure for physical goods shopping of US$5,800 to $16,000, with a mean of $10,000 (BLS 2009). The 2009 NHTS further yielded an estimate of 1,900 miles (3,058 km) driven by the average driver for shopping purposes, and, combined with fuel economy estimates from above, this produced a range of 0.03 to 0.14 kg CO_2e/US$ shopping expenditure. For an average physical album cost of $15, this yielded a range of 0.5 to 2 kg CO_2e/album, with a mean of 1.1. Thus, this validity check led to a slightly lower mean estimate and smaller range than the assumed method; however, a sensitivity analysis on the results showed that both allocation methods led to similar conclusions.

Warehouse Energy Usage

Energy use in warehouses was again taken from a previous study of e-commerce logistics (Weber et al. 2009a), which used private data as well as public data from the Commercial Buildings Energy Consumption Survey (CBECS; DOE 2003). CBECS is a large survey done by the Department of Energy that estimates energy intensities for various types of commercial businesses, including retail stores. These data sources summarize the average sales (in dollars) and size (in square feet) for many types of businesses.

Energy Usage in Retail Stores

Data on energy use of retail stores came from Bizstats and the Commercial Buildings Energy Consumption Survey. Bizstats reports that the average retail sales are $250 to $900 per square foot ($ft^2$; Bizstats 2008).[4] For energy use, the Commercial Buildings Energy Consumption Survey (DOE 2003) was used. Given our data needs, we allocate energy use instead by dollars of sales, which results in an estimated energy use value in megajoules per dollar, which ranged from 0.03 to 0.14 MJ/$ for nonmall stores (at $900/$ft^2$) and 0.07 to 0.17 MJ/$ for retails stores in malls (DOE 2003). We assume a retail price of $15 per CD to convert these intensities into megajoules of energy uses in the retail phase.

Internet Energy Use for Download and Data Transfer

To estimate the electricity intensity of data downloaded over the Internet, we use the methodology first presented by Koomey and colleagues (2004) and further developed by

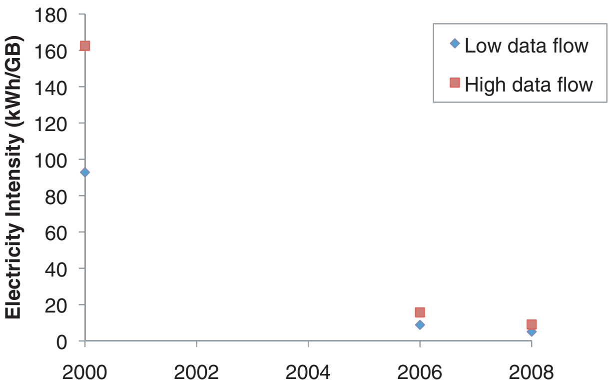

Figure 4 Internet electricity intensity for transferring data (kilowatt-hours per gigabyte [kWh/GB] transferred) at times of low and high data flow.

Taylor and Koomey (2008). Taylor and Koomey estimated the electricity intensity of information transfers in kilowatt hours per gigabyte (GB) for 2000 and 2006 (see figure 4).[5] We updated the 2006 estimate to 2008 by assuming total Internet data flows from 2006 to 2008, as described in the Supplementary Material on the Web. These assumptions resulted in an average electricity intensity of Internet data flows of about 7 kWh per gigabyte transferred for 2008. This intensity drops about 30% per year, or halves every 2 years (see figure 4). We assume a range of album size from 60 to 100 megabytes (MB), on the basis of inspection of a commonly used online music site (the iTunes store). We also assume 1 to 2 MB data transfer for online shopping and purchasing.

Energy Usage in Homes for Placing e-Commerce Orders

The consideration of home computer energy use in studies of e-commerce has varied over time (Toffel and Horvath 2004; Turk et al. 2003; Sivaraman et al. 2007). Past work has included the energy of the computer and monitor (often desktop computers, despite the high prevalence of laptops today); lighting, heating, and cooling in the room; and the network energy overhead for the transaction. We assume a range of 40 to 200 watts (W) site energy for an average computer[6] and assume that a person spends an average of 11 to 20 minutes shopping online for the album, allocated fully to the purpose of buying the album (Turk et al. 2003). This represents an upper bound estimate, although computer users often perform multiple tasks at once. We also include an allocated share of the production energy of the computer (0.004 kWh/minute), using an assumed lifetime of 3 years, because previous work has shown the importance of the production phase for computers (Toffel, 2004; Williams, 2004). We use a similar method as above for data transfer during online shopping (see the *Internet Energy Use for Download and Data Transfer* section). We assume an upper bound value of 1 MB data usage for the online shopping and purchasing. These ranges lead to an estimate of 1 to 2 MJ of primary energy use from the consumer placing the order online.

Results

The main results for the six scenarios can be seen in figure 5, for primary energy (megajoules) per album, top, and CO_2 emissions (grams of CO_2) per album, below. Error bars represent the 90% credible intervals[7] (i.e., 5th and 95th percentiles of output distributions) from the Monte Carlo uncertainty analysis.

The graphs show that the mean rank order of scenarios was the same for primary energy and CO_2 emissions, with the retail method taking the most energy and emissions, followed by the two e-commerce scenarios, and with the three download scenarios using the least amount of energy and producing the least CO_2 emissions. We find a range from a high of 53 MJ/album and 3,200 g CO_2/album for the retail scenario to 7 MJ/album and 400 g CO_2/album for the download with no

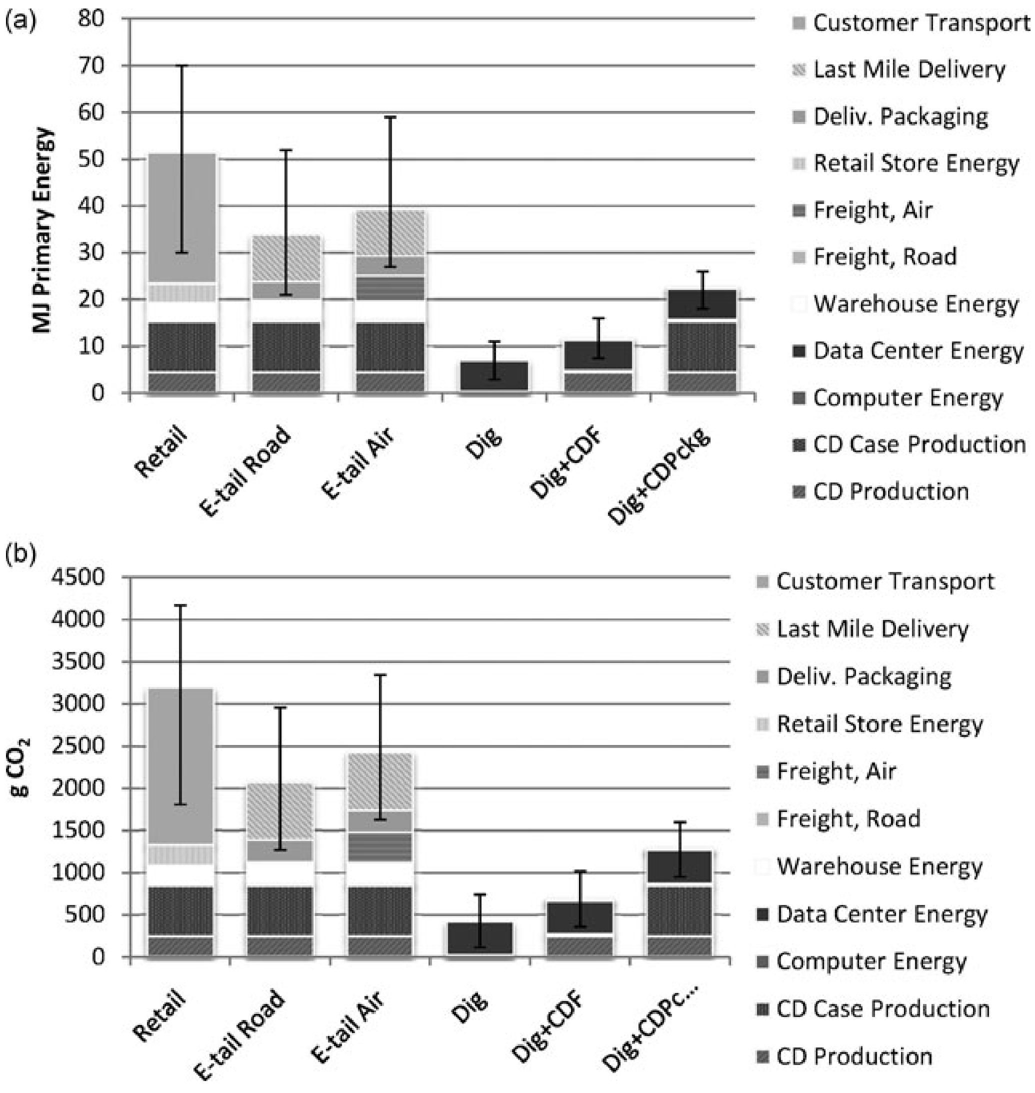

Figure 5 Comparison of six album purchase scenarios in cumulative energy (megajoules [MJ] per album, top) and carbon dioxide (CO_2) emissions (grams CO_2 [g CO_2] per album, bottom). Scenarios are listed in numerical order (Scenario 1, left, to Scenario 6, right). Error bars represent 90% credible intervals from Monte Carlo analysis. Deliv. = delivery; Dig = digital download; Dig+CDF = digital download with the file burned to a CD; Dig+CDFPckg = digital download with the file burned to a CD and stored in individual CD packaging.

CD burning scenario ("Dig" in figure 5). Thus, we find slightly less than an order of magnitude difference between the worst and best scenarios for artist to customer album delivery. It should be noted that the best physical CD option, Scenario 2, still uses 62% more energy and produces 64% more CO_2 emissions than the worst download option, Scenario 6. Given the very similar results for energy and CO_2, we now focus purely on CO_2 emissions.

The production of CDs and CD packaging represents between 32% (Scenario 1) and 69% (Scenario 6, with very low logistics energy) of the album delivery, which shows that the logistics chain of getting the physical CD to the customer is even more important than the

Table 1 Correlation coefficients of importance for uncertainty assessment in total greenhouse gas (GHG) emissions from the six purchase scenarios.

Parameter	*Retail*	*E-commerce road*	*E-commerce air*	*Dig*	*Dig+CDF*	*Dig+CD +pckg*
Driving distance	0.71^{*}					
Fuel economy	-0.33^{*}					
Warehouse: electricity	0.09	0.11^{*}	0.11^{*}			
Retail: gas	0.04					
Jewel case production	0.59^{*}	0.85^{*}	0.81^{*}			0.06
CD production	0.07	0.07	0.07		0.23^{*}	0.23^{*}
Last-mile energy		0.49^{*}	0.47^{*}			
Data centers		0.07	0.06	0.99^{*}	0.96^{*}	0.95^{*}
Computer energy		0.07		0.05	0.06	0.06
E-tail packaging		0.13^{*}	0.12^{*}			
E-tail road freight		0.05				
E-tail air freight			0.29^{*}			

Note: Asterisks denote a correlation with an absolute value above 0.1. Dig = digital download; Dig+CDF = digital download with the file burned to a CD; Dig+CDF+pckg = digital download with the file burned to a CD and stored in individual CD packaging.

"dematerialization" of eliminating CD and CD packaging production. Similar to previous studies (Matthews et al. 2001, 2002; Sivaraman et al. 2007), we find customer transport to the retail store and last-mile delivery for e-commerce to be major contributors: 52% of Scenario 1 and 24% to 28% of Scenarios 2 and 3, respectively. In addition, warehouse energy use, retail store energy use, and individual shipping packaging for e-commerce contribute notable amounts to the physical CD delivery scenarios. Besides CD and slimline case production for Scenarios 5 and 6, the energy and emissions associated with the download scenarios are almost completely due to upstream data center energy usage for data transfer—home computer usage is relatively unimportant, as are logistics of CD-R and CD case purchase. The impacts of producing CD packaging are smaller for Scenario 6 than for Scenarios 1–3, due to the smaller mass of the slimline CD case. These requirements are minor, regardless of whether CD-Rs and cases are purchased through retail or e-tail, due to the assumed bulk delivery of 50 packs.

The results of the Monte Carlo analysis also provide insight into the relative importance of different parameters in the overall uncertainty of the album delivery scenario's emissions. Table 1 shows correlation coefficients of individual parameters with total delivery emissions, a rough measure of the importance of each parameter to the overall uncertainty and variability of the system. In summary, a large correlation coefficient means an uncertain variable is particularly important to the overall uncertainty of the total emissions associated with the delivery scenario. For the retail delivery system, as would be expected, two of the most important parameters were driving distance from home to retail store and fuel economy of the automobile taken, with minor importance from warehouse energy use and CD production. Jewel case production was also very important for uncertainty and variability, due to the large range of types of packaging assumed (Liverman 2009). For the same reason, jewel case production dominated variability in e-commerce routes, with uncertainties in last-mile delivery, shipping packaging, and warehouse energy use following. For the digital routes, nearly all uncertainty and variability had to do with upstream data center energy, a combination of uncertainty due to energy per megabyte flow as well as the carbon intensity of electricity.

Because the high end of the uncertainty range for the worst download scenario (Scenario 6) overlaps with the low end of the uncertainty range for the best physical CD scenario (Scenario 2), we also show the simulated difference

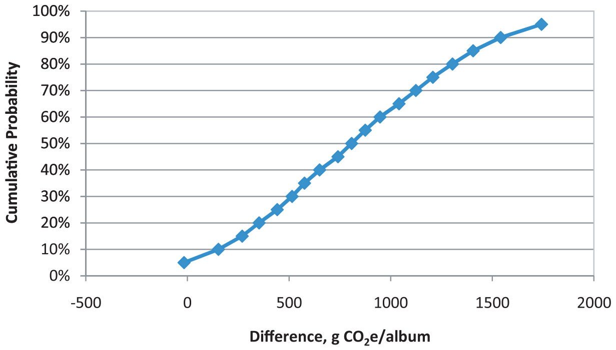

Figure 6 Simulated cumulative distribution of difference between carbon dioxide (CO_2) emissions from e-tail Scenario 2 and download Scenario 6 (grams CO_2/album [g CO_2e/album]).

between Scenarios 2 and 6 in a cumulative probability curve in figure 6. As seen in figure 6, fewer than 7% of simulations produced a negative difference (i.e., a simulation in which Scenario 6 produced more CO_2 emissions than Scenario 2). Thus, despite the fact that the uncertainty ranges overlap, only in extreme cases of either Scenario 2 or Scenario 6 does the digital download Scenario 6 produce more CO_2 emissions than the e-tail Scenario 2.

Discussion and Future Work

Given the assumptions of the analysis, the results are fairly clear—downloading albums uses less energy and produces fewer CO_2 emissions than purchasing a physical CD by either traditional retail or e-commerce methods. The difference between even the worst-case scenario (Scenario 6) for downloading and the best-case scenario for physical CD purchase is rather large—around 65% more CO_2 emissions from purchasing an album from an e-tail site compared with downloading an album, burning it to CD-R, and storing it in a slimline jewel case. Given the results of the Monte Carlo analysis, these results seem robust.

It is, however, relevant to ask what variable values would flip the result and make the download option more CO_2-intensive than e-tail purchase. Of course, the six scenarios here do not describe all potential ways an album can be delivered from recording to a final consumer. We investigated several variables to see at what point their values would produce equivalent emissions between downloading and either e-tail or retail. The first and most obvious case is reducing consumer transportation to a retail store. In the extreme case, in which the trip to the store produces no emissions (i.e., walking or biking, with no assumed additional food requirements), the retail system produces a mean of 1,330 g CO_2, still slightly higher than Scenario 6 but, given uncertainties, basically the same. Although walking to the store may be common in densely populated areas, it can be considered unlikely in suburban or rural areas, where half of the U.S. population lives (U.S. Census 2007).

We also investigated how file size and time spent shopping online could increase emissions from the online purchase scenarios to the mean e-tail Scenario 2 (an increase of around 800 g CO_2/album). If file size remains constant, even the most energy-intensive computer assumed (200 W) would require more than 5 hr of Web browsing to increase Scenario 6 by this amount. Thus, it is unlikely that this variable alone could change the result. For file size, it was estimated that an album size of 260 MB would increase the emissions associated with Scenario 6 to equivalence with Scenario 2. Unlike the 5-hr browsing scenario, this data transfer is entirely plausible if online music stores move toward "lossless" digital audio formats in large number, such as Microsoft's WMA 9 lossless format. We assume in this analysis that audio quality in the standard MP4 format, which produces albums from 60 to 100 MB, is good enough for most listeners, but as more homes get high-fidelity home theater systems, this may no longer be true. It is also critical to remember, however, that the energy intensity of file transfers is dropping 30% per year (see *Internet Energy Use for Download and Data Transfer* section), and thus the equivalent file size is growing by approximately 30% per year concurrently. CD manufacturing and logistics systems may also be getting more energy efficient with time, though, which thus makes the difference between the two systems a moving target.

A main limitation of this work is the assumption of equivalence between downloading an album and purchasing the album in CD form. Although this assumption is convenient, in reality it is likely that customers use physical and digital albums somewhat differently, and these differences may be critical for the analysis, as discussed previously (Turk et al. 2003). One issue is fidelity, as discussed above. Another is the importance of album artwork, which is not explored here. Although many download services offer a digital version of the album artwork with the download, this may not be completely satisfactory for some customers. Furthermore, we did not include any production impacts associated with digital music players, which could reasonably be attributed to the online music system (although users can, of course, rip CDs to digital music players as well). We also neglected emissions from the production of standard CD players, which are generally longer lived than MP3 players but still involve significant production emissions. In addition, we did not consider potential income rebound effects associated with online music, which tends to cost less than traditional CDs; this could affect the results (Hertwich 2005). Finally, it is likely that users either purchase or store music in different units than albums—for instance, either storing multiple albums per CD-R or downloading single tracks as opposed to whole albums (Hogg and Jackson 2008). Future work assessing these behavioral aspects would be extremely valuable.

Also, this study is limited to one potential online music system, a purchase-for-download system, as is currently common in Amazon's MP3 service and the iTunes store. Many more systems exist, however, such as subscription systems whereby the user pays a fee per month for access to a catalog of albums that can then be streamed at will. Clearly this is an entirely different system, and future work should elucidate the energy and emissions associated with streaming audio. Furthermore, streaming video is also a relatively unexplored area and is growing extremely quickly in Internet traffic. Extending previous studies on video rental (e.g., Sivaraman et al. 2007) to include both downloadable digital video rentals and streaming video systems would also be informative for tech-savvy customers.

Conclusions

In this study, we analyzed the energy and CO_2 emissions associated with delivering music from a recording studio to a final customer by traditional retail, e-tail, and download routes. Given our assumptions, our results indicate the superiority of downloadable online music, which even in the worst-case scenario produces, on average, 65% lower CO_2 emissions than the best-case e-tail delivery method. Significantly higher savings (nearly a factor of 5) can be seen if the customer forgoes CD-R burning in favor of fully digital use, which thereby eliminates the energy needed to produce the CD and its packaging. The results are, however, sensitive to both behavioral assumptions of how customers use digital music and several important parameters in the logistics chain of retail and e-tail delivery, such as customer transport to the store, CD packaging method, and final delivery to the customer's home for e-tail. In particular, online music's superiority depends on the assumption that customers drive automobiles to the retail store. Future work should focus on new methods for digital media acquisition, such as subscription and streaming services, which may increase the energy requirements of downloading digital goods.

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Notes

1. One gram (g) = 10^{-3} kilograms (kg, SI) ≈ 0.035 ounces (oz); one kilowatt-hour (kWh) ≈ 3.6×10^6 joules (J, SI) ≈ 3.412×10^3 British Thermal Units (BTU).

2. One megajoule (MJ) = 10^6 joules (J, SI) ≈ 239 kilocalories (kcal) ≈ 948 British Thermal Units (BTU).
3. One kilogram (kg, SI) ≈ 2.204 pounds (lb).
4. One square foot (ft^2) ≈ 0.093 square meters (m^2, SI).
5. One gigabyte (GB, SI) = 10^3 megabytes (MB) = 10^9 bytes.
6. One watt (W, SI) ≈ 3.412 British Thermal Units (BTU)/hour ≈ 1.341×10^{-3} horsepower (HP).
7. The term *credible intervals* is used in Bayesian statistics to describe posterior probabilities of variables given Bayesian updating. Although it is not strictly comparable to Monte Carlo simulated results as here, we use the term to describe the 90% probability bands for variables.

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Supplementary Material

Additional Supplementary Material may be found in the online version of this article:

Supplement S1: This supplement contains included and excluded variables in scenarios (Supplementary Appendix S1–1), detailed data and methods (Supplementary Appendix S1–2), and assumed input parameters and distributions for analysis (Supplementary Appendix S1–3).